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URI FINAL TECHNICAL REPORT

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Research in Chaotic and Turbulent Fluid Dynamics
by Professor Aref and associates

As indicated below twenty refereed papers in journals and conference proceedings volumes acknowledge the DARPA/URI. Twenty-six presented papers cited support by this grant. The research peformed falls mainly in the following three subject areas:

1. Fundamental problems in vortex dynamics

Additional results on both integrable and chaotic point vortex dynamics have been obtained. These include the elucidation of chaotic scattering within point vortex systems [6], the discovery of a particularly simple integrable case for the three-vortex problem [9], and the exploration of the relationship between vortex sound emitted by interacting point vortices and complex time singularities [12]. Suggestions have been made on the role that chaos in vortex interactions may play in 'real' flows, such as shear layers and wakes [1], and how turbulence can be viewed as a dynamical system of interacting vortices [20]. Overview articles have been written at different levels for various audiences [3,4,5,10,14]. In 3D a major result has been the discovery through numerical experiments of a mechanism whereby initially unlinked vortex rings can link, thus creating helicity [19].

2. Vortex methods for 3D simulations

In order to perform 3D vortex interaction simulations it was necessary to develop a 3D version of the vortex-in-cell methodology that is well known in 2D. This development effort was the subject of the PhD thesis of I. Zawadzki. The code produced was used to study vortex ring reconnections [13], including topology change and scalar mixing [18,19].

3. Chaotic advection in fluid flows

A key theme in the application of dynamical systems ideas to fluid flows has been the notion of chaotic advection, introduced by Aref in 1984. Elaboration and exploration of chaotic advection scenarios in intermediate and high Re flow models resulted in several papers. In [2] the extreme sensitivity of numerical flow solutions involv ıg Lagrangian data was used to argue against cellular automaton methods. New applications of chaotic advection were discussed, e.g., separation of particles [8], and mixing due to secondary flows [11]. Several general reviews of this very active subject were written [15,16,17].

Journal papers and conference proceedings supported by DARPA/URI

1. H. Aref, M. Gharib & C. W. Van Atta, "Chaos in shear flows." Paper *AIAA-87-1251* (1987).
2. H. Aref, S. W. Jones & G. Tryggvason, "On Lagrangian aspects of flow simulation." *Complex Systems* **1**, 544-558 (1987).
3. H. Aref & T. Kambe, "Report on the IUTAM Symposium: Fundamental aspects of vortex motion." *J. Fluid Mech.* **190**, 571-595 (1988).
4. H. Aref, J. B. Kadtke, I. Zawadzki, L. J. Campbell & B. Eckhardt, "Point vortex dynamics: Recent results and open problems." *Fluid Dyn. Res.* **3**, 63-74 (1988).
5. H. Aref, S. W. Jones & O. M. Thomas, "Computing particle motions in fluid flows." *Computers in Physics* **2**(6), 22-27 (1988).
6. B. Eckhardt & H. Aref, "Integrable and chaotic motions of four vortices II: Collision dynamics of vortex pairs." *Phil. Trans. Roy. Soc. (London) A* **326**, 655-696 (1988).
7. H. Aref & G. Tryggvason, "Model of Rayleigh-Taylor instability." *Phys. Rev. Lett.* **62**, 749-752 (1989).
8. H. Aref & S. W. Jones, "Enhanced separation of diffusing particles by chaotic advection." *Phys. Fluids A* **1**, 470-474 (1989).
9. H. Aref, "Three-vortex motion with zero total circulation: Addendum." *J. Appl. Math. Phys. (ZAMP)* **40**, 495-500 (1989).

10. H. Aref, S. W. Jones, S. Mofina & I. Zawadzki, "Vortices, kinematics and chaos." *Physica D* **37**, 423-440 (1989).
11. S. W. Jones, O. M. Thomas & H. Aref, "Chaotic advection by laminar flow in a twisted pipe." *J. Fluid Mech.* **209**, 335-357 (1989).
12. Y. Kimura, I. Zawadzki & H. Aref, "Vortex motion, sound radiation, and complex time singularities." *Phys. Fluids A* **2**, 214-219 (1990).
13. H. Aref & I. Zawadzki, "Comment on vortex ring reconnections." In *Topological Fluid Mechanics,* H. K. Moffatt & A. Tsinober eds., Cambridge University Press, pp.535-539 (1990).
14. H. Aref, "Chaotic fluid dynamics and turbulent flow." In *Whither Turbulence? Turbulence at the Crossroads* J. L. Lumley ed., *Lect. Notes Phys.* **357**, 258-268 (1990) Springer-Verlag.
15. H. Aref, "Stirring by laminar flow, dynamical systems, and chaotic advection." Proceedings of *Fluids Engineering and Science: The US-Korea Joint Seminar,* Hemisphere Publishing Corp., Washington D.C., pp.151-162 (1991).
16. H. Aref, "Chaotic advection of fluid particles." *Phil. Trans. Roy. Soc. (London) A* **333**, 273-289 (1990).
17. H. Aref, "Stochastic particle motion in laminar flows." *Phys. Fluids A* **3**, 1009-1016 (1991).
18. I. Zawadzki & H. Aref, "Mixing during vortex ring collision." *Phys. Fluids A* **3**, 1405-1410 (1991).
19. H. Aref & I. Zawadzki, "Linking of vortex rings." *Nature* **354**, 50-53 (1991).
20. H. Aref & I. Zawadzki, "Vortex interactions as a dynamical system." Proceedings of the *Monte Verità Colloquium on Turbulence.* Ascona, Switzerland. Birkhäuser (In Press).

Presentations acknowledging DARPA/URI (unpublished, or abstract only)

1. H. Aref, "The digital Hele-Shaw cell." Invited presentation, *Workshop on Vortex Dynamics,* UCLA, May 1987.
2. H. Aref, "The digital Hele-Shaw cell." Invited presentation, *Fifth International Conference on Numerical Methods for Laminar and Turbulent Flow,* Montreal, Canada, July 1987.
3. H. Aref, "Chaotic advection." Invited presentation, 37th Symposium of Industrial Affiliates Program *Disordered Materials, Fractals and Chaos,* Departments of Chemistry and Chemical Engineering, Stanford University, September 1987.
4. S. W. Jones, O. M. Thomas & H. Aref, "Chaotic advection by laminar flow in a twisted pipe." Fortieth *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* University of Oregon. Abstract in *Bull. Amer. Phys. Soc.* **32**, 2026 (1987).
5. I. Zawadzki & H. Aref, "Collision dynamics of vortex pairs." Fortieth *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* University of Oregon. Abstract in *Bull. Amer. Phys. Soc.* **32**, 2062 (1987).
6. H. Aref, "Vortices, kinematics and chaos." Second Annual *Stanley Corrsin Memorial Lecture in Fluid Mechanics,* The Johns Hopkins University, May 1988.
7. H. Aref, "Chaotic advection." ASME/SES *Symposium on Chaotic and Turbulent Flows,* UC Berkeley, June 1988. Invited presentation.
8. H. Aref, "Chaotic advection." Workshop on *The Lagrangian Picture of Fluid Mechanics,* University of Arizona, Tucson, October 1988. Invited presentation.
9. H. Aref, "Stirring by laminar flow, dynamical systems, and chaotic advection." Invited lecture at Workshop on *Applying Non-Linear Dynamics and Chaos in Fluid Mechanics,* Woudschoten Conference Centre, Zeist, The Netherlands, June 1989.
10. H. Aref, "Integrable and chaotic motion of point vortices." Invited lecture, *Dynamics Days Düsseldorf,* Federal Republic of Germany, June 1989.

11. H. Aref, "Chaotic advection." *ASME Forum on Chaotic Flows,* La Jolla, CA, June 1989.
12. K. Sheth & H. Aref, "Chaotic scattering of rays from reflecting fluid surfaces." Forty-second *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* NASA Ames Research Center. Abstract in *Bull. Amer. Phys. Soc.* **34**, 2286 (1989).
13. I. Zawadzki & H. Aref, "Simulation of vortex ring reconnection using a vortex-in-cell method." Forty-second *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* Palo Alto. Abstract in *Bull. Amer. Phys. Soc.* **34**, 2295 (1989).
14. Y. Kimura, I. Zawadzki & H. Aref, "Vortex motion, sound radiation, and complex time singularity."Forty-second *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* Palo Alto. Abstract in *Bull. Amer. Phys. Soc.* **34**, 2308 (1989).
15. N. Rott & H. Aref, "Three-vortex motion with zero total circulation." Forty-second *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* Palo Alto. Abstract in *Bull. Amer. Phys. Soc.* **34**, 2308 (1989).
16. H. Aref, "Chaotic advection in vortex flows." Euromech 261: *First Symposium on Görtler Vortex Flows.* Nantes, France, June 1990. Keynote lecture.
17. H. Aref, "Enhanced separation of diffusing particles by chaotic advection." NSF/AFOSR Workshop on *Transport Enhancement by Chaotic Advection.* La Jolla, August 1990.
18. H. Aref, "Numerical experiments on chaotic advection." *Second World Congress on Computational Mechanics.* Stuttgart, FRG, August 1990. Keynote address on *Chaos and its Numerical Analysis.*
19. H. Aref, "Lagrangian CFD." *Australasian Congress of Applied Mathematics.* New Zealand, February 1991. Opening lecture.
20. H. Aref, "The role of chaos in fluid mechanics" and "Fluid mechanics of soap films, bubbles and foams." *Westinghouse Distinguished Lectureship,* The University of Michigan, March 1991.
21. H. Aref, "Chaotic advection: Application of chaos to stirring and mixing." *American Physical Society March Meeting,* Division of Fluid Dynamics symposium, Cincinnati, March 1991. Invited presentation. Abstract in *Bull. Amer. Phys. Soc.* **36**, 903-904 (1991).
22. H. Aref, "Vortex interactions as a dynamical system." Workshop on *Dynamics of Structures and Intermittencies in Turbulence.* Arizona State University, Tempe, May 1991. Invited presentation.
23. H. Aref, "Lagrangian methods in computational fluid dynamics." Conference on *State-of-the-Art in Computational Fluid Mechanics.* INTEVEP Headquarters, Venezuela, May 1991. Invited presentation.
24. H. Aref, "Chaos in fluid mechanics from the Lagrangian point of view." *Third Soviet-American Workshop on Chaos.* National Academy of Sciences Study Center, Woods Hole, July 1991. Invited presentation.
25. H. Aref, "Grand challenges: Research frontiers." *Summer Institute on CFD,* San Diego Supercomputer Center, August 1991. Invited presentation.
26. I. Zawadzki & H. Aref, "Numerical experiments on vortex ring collisions." Forty-fourth *Annual Meeting of the American Physical Society, Division of Fluid Dynamics,* Scottsdale, AZ, November 1991. Abstract in *Bull. Amer. Phys. Soc.* **36**, 2693 (1991).

URI final report

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My program under the URI was primarily one of studying vortex dynamics. This involved the study of ensembles of vortices as a model of two-dimensional turbulence, vortex stability, and vortex interaction with the environment.

For the question of the evolution of two-dimensional turbulence, I collaborated with Bill Young, J.C. Mcwilliams, Y. Pomeau, and J.B. Weiss. In Carnevale et al. 1991, we provided a new scaling theory for decaying two-dimensional turbulence based entirely on vortex statistics. This theory was compared successfully to high resolution simulations and recently verified by laboratory experiments (Tabeling et al. 1991). In addition to the scaling theory, we also introduced a model for decaying turbulence based on point vortices which can undergo mergers according to ad hoc rules. We believe this model will be very useful in further exploring two-dimensional turbulence. Recently, Montgomery et al (1992) published the result of a long simulation (600 Cray hours) which shows for the first time the end-state of decaying two-dimensional turbulence. The result is a pair of counter-rotating vortices. We have shown how to use our new theory to predict the size and strength of these vortices in Carnevale et al. (1992).

On the question of stability of vortices, we have recently proven the formal stability of a family of vortices that previously had only been shown to be linearly stable (Kloosterziel and Carnevale 1992a). This is a major step forward since it opens the door for a proof of fully nonlinear stability. The vortices involved are those consisting of an annulus of vorticity of one sign surrounding a circular patch of vorticity of the opposite sign. We also investigated a new method for finding stable states of any fluid. This is the method we call pseudo-advection and we have shown that it can be generalized to any Hamiltonian system.

We also investigated the effect of topography on vortex propagation and production. We showed how topography alters the trajectories of dipoles and monopoles and tested the predictions through numerical simulations and in laboratory experiments. This work may find application in the propagation of dipoles on continental shelfs and to the question of magnetic confinement of neutral plasmas where it has been conjectured that dipoles can carry away significant quantities of energy.

Other works included studies of three dimensional vortex dynamics, fluctuation-dissipation relations for chaotic systems, atmospheric predictability, dipole stability, and statistical mechanics of a two-fluid plasma model.

References

Montgomery D., Matthaeus W.H, Stribling W.T., Martinez D., Oughton S., and Montgomery D. 1992, Selective decay and coherent vortices in incompressible turbulence, Phys. Rev. Lett. **66**, 3-6.

Tabeling P., Burkhart S., Cardoso O., and Willaime H. 1991. Experimental Study of Freely decaying two-dimensional turbulence. Phys. Rev. Lett. **67**, 3772-3775.

Publications from work supported by the URI:

Publications in refereed journals:

Carnevale G.F., Vallis G.K., Purini R., and Briscolini M. 1988, "Propagation of Barotropic Modons over Topography " Geophys. Astrophys. Fluid Dyn. **41**, 45-101.

Carnevale G.F., Briscolini M., Purini R., and Vallis G.K., 1988, "Numerical Experiments on Modon Stability to Topographic Perturbations" Phys. Fluids. **31**, 2562-2566.

Carnevale G.F., Vallis G.K., Purini R., and Briscolini M. 1988, "The Role of Initial Conditions in Flow Stability, with Applications to Modons " Phys. Fluids. **31**, 2567-2572.

Vallis G.K., Carnevale G.F. and Young W., 1989, "Extremal energy properties and construction of stable solutions of the Euler equations," J. Fluid Mech. **207**, 133-152.

Benzi R. and Carnevale G.F., 1989, "A possible measure of enhanced predictability," J. Atmos. Sci. **46**, 3595-3598.

Carnevale G.F. and Shepherd T.G., 1990, "On the interpretation of Andrews' theorem," Geophys. Astrophys. Fluid Dyn. **51**, 1-17.

Carnevale G.F. and Vallis G.K. 1990, "Pseudo-advective relaxation to stable states of inviscid two-dimensional flow," J. Fluid Mech. **213**, 549-571.

Carnevale G. F., Pomeau Y., and Young W., 1990, "Statistics of ballistic agglomeration," Phys. Rev. Letters **64**, 2913-2916.

Carnevale G. F., Cavazza P., Purini R., and Orlandi P., 1991, "An explanation for anomalous vortex merger in rotating tank experiments," Physics of Fluids A **3**, 1411-1415.

Koniges A.E., Crotinger J.A., Dannevik W.P., Carnevale G.F., Diamond P.H., and Gang F.Y. 1991, "Equilibrium spectra and implications for a two-field turbulence model," Physics of Fluids B **3**, 1297-1299.

Carnevale G. F., McWilliams J.C., Pomeau Y., Weiss J.B., and Young W.R., 1991, "Evolution of vortex statistics in two-dimensional turbulence," Phys. Rev. Letters **64**, 2735-2737.

Carnevale G. F., M. Falcioni, S. Isola, Purini R., and Vulpiani A., 1991, "Fluctuation-dissipation relations in systems with chaotic behavior," Physics of Fluids A **3**, 2247-2254.

Carnevale G. F., Kloosterziel R., Van heijst G-J, 1991, "Propagation of barotropic vortices over topography in a rotating tank," J. Fluid Mech. **233**, 119-139.

Carnevale G.F., McWilliams J.C., Pomeau Y., Weiss J.B., and Young W.R., 1992, "Rates, pathways, and end-states of nonlinear evolution in decaying two-dimensional turbulence: scaling theory vs. selective decay" Physics of Fluids A **4**, 1314-1316.

Kloosterziel R.C. and Carnevale G. F., 1992, "Formal stability of circular vortices," J. Fluid Mech. **242**, 249-278.

Edited Book:

Pierrehumbert R. and Carnevale G.F., 1992 (editors), Nonlinear Phenomena in Atmospheric and Oceanic Sciences, Proceedings of the IMA workshop, June 5, 1990 (Springer-Verlag, New York)

Publications in conference proceedings:

Carnevale G.F., Purini R., Briscolini M. and Vallis G.K., 1989, "Influence of topography on modon propagation and survival," in **Mesoscale/Synoptic Coherent Structures in Geophysical Turbulence** , pp. 181-195 ed's. J.C.J. Nihoul and B.M. Jamart (Elsevier, Amsterdam),

Carnevale G.F. and Vallis G.K. 1989, "Quenching two-dimensional flows", proceedings of the Woods Hole Oceanographic Institution Summer Program, 8/88

Carnevale G.F. and Vallis G.K. 1990, "Isovortical energy variation in two-dimensional flows," in Topological Fluid Mechanics, Proceedings of the IUTAM conference on Topological Fluid Dynamics 1989 (Eds. H.K. Moffat and A. Tsinober, Cambridge)

Vallis G.K., Carnevale G.F. and Shepherd T.G. 1990, "A natural method for finding stable states of Hamiltonian systems," in Topological Fluid Mechanics, Proceedings of the IUTAM conference on Topological Fluid Dynamics 1989 (Eds. H.K. Moffat and A. Tsinober, Cambridge)

Briscolini M., Benzi R., Carnevale G.F., Santangelo P., and Succi S. 1990, "Numerical simulations of three-dimensional flows," in Supercomputing Tools for Science and Engineering (Eds. D. Laforenza and R. Perego, Pub. Franco Angeli Libri, Milan, Italy)

DARPA, URI FINAL REPORT

M. Gharib and Company

Our research efforts had two prongs. The focus of the first part was understanding the onset of chaos and turbulence in fluid mechanical systems. The focus of the second part was to develop advanced diagnostic systems in order to facilitate to experimental approaches of the first part.

The research efforts in the first part focused on three topics, namely jets, wakes and vortex rings. These elemental flows are building blocks of every complex turbulent flow system. Therefore, understanding of their behavior under natural and controlled conditions is of paramount importance. All three systems were approached as dynamically dissipative systems. Thus, in conjunction with our other colleagues at INLS, attempts were made to model these systems as low dimensional dynamical system. Such an approach helped us to use tools from dynamical system theory to examine pre-transitional stages of route to turbulence.

In the course of the second effort we designed and fabricated various global imaging systems that enabled us to map scalar and vector fields simultaneously. Therefore, such devices helped us to study Lagrangian and Eulerian behavior of the flow and various routes to chaos through quantitative flow visualization of the aforementioned elemental shear flows.

The enclosed diagram demonstrates the organizational structure of our research group and its connection to various other research groups. In the following sections each effort is briefly described.

1. Experiments on the forced wake of an airfoil

The effect of initial flow conditions on the wake of an airfoil is examined in an experiment which uses the 'strip heater' technique to externally force the airfoil wake. The strip heaters are used to introduce waves into the top and bottom boundary layers of a thin symmetric airfoil which are subsequently amplified and introduced to the wake. The evolution and interaction of the waves in the wake is the primary interest of this study. A linear stability analysis is applied to the mean velocity profiles in order to understand the

frequency selection process in the wake. It is seen that the mean velocity profile adjusts itself in order to become more receptive to the forced frequency of oscillation, resulting in the suppression of previously existing frequencies. The amplitude of oscillations in the wake can be controlled by varying the phase relation between two input signals. In this respect, cancellation and enhancement of the oscillations is possible. The linear stability analysis is applied to the cancellation/enhancement flow to verify the level of cancellation achieved. The receptivity of the system to external forcing is established. A substantial reduction in drag is achieved for forcing frequencies near the centre of the receptivity range.

2. Transition from order to chaos in the wake of an airfoil

An experimental effort is presented here that examines the nonlinear interaction of multiple frequencies in the forced wake of an airfoil. Wakes with one or two distinct frequencies behave in an ordered manner - being either locked or quasi-periodic. When a third incommensurate frequency is added to the system, the flow demonstrates chaotic behavior. Previously, the existence of the three-frequency route to chaos has been reported only for closed system flows. It is important to note that this chaotic state is obtained at a low Reynolds number. However, the chaotic flow shows localized characteristics similar to those of high Reynolds number turbulent flows. The degree of chaotic behavior is verified by applying ideas from nonlinear dynamics (such as Lyapunov exponents and Poincaré sections) to the experimental data, thus relating the basic physics of the system to the concepts of mode interaction and chaos. Significant changes to the vortex configuration in the wake and to the r.m.s. velocity profile occur during the transition from order to chaos.

3. Structure of ordered and chaotic vortex streets behind circular cylinders at low Reynolds numbers

We have investigated the spatial and temporal structure of certain cases of chaotic and organized vortex shedding in self-excited cylinder wakes at low Reynolds number (40-200) by extending hot-wire measurements to much larger downstream locations than our earlier measurements (Van Atta and Gharib, 1987) and performing concurrent smoke-wire flow

visualizations. We describe here results for two cases in which chaotic vortex shedding is observed. The first is the single-vibration frequency locked-in case, in which the most highly disturbed regions of the vortex street, which produce chaotic spectra, are confined to compact spanwise-periodic propagating disturbed regions. The second is the multiple-vibration frequency case in which chaotic velocity spectra are observed at all spanwise locations.

4. Cross-Bispectral analysis of a vibrating cylinder and its wake in low Reynolds number flow

Cross-bispectral analysis is used to investigate the coupling between a slender vibrating cylinder and the velocity field in its wake at low Reynolds numbers $[Re = 0(10^2)]$. The velocity field was characterized by a complicated power spectrum, with low frequency peaks as well as upper and lower side band peaks near the primary Strouhal frequency peak and its harmonics. Power spectral and cross-bispectral analyses indicate that the rich structure of the wake velocity power spectra is a direct consequence of the vibrating cylinder. The data suggest the cylinder is coupled to its wake in the sense that the cylinder vibrations introduce motions into the wake at the vibration frequency, and these motions interact nonlinearly within the wake to produce fluctuations at other frequencies. Cross-bispectral analysis isolates the interactions between cylinder vibrations and wake fluctuations.

5. An experimental study of the parallel and oblique vortex shedding from circular cylinders and development of a novel method to promote parallel vortex shedding in the wake of circular cylinders

An experimental study of the origin of oblique vortex shedding in the laminar wake of circular cylinders was conducted in the range of Reynolds numbers from 40 to 160. Two

transverse circular cylinders were positioned upstream of the main shedding cylinder to control the angle of shedding from the main cylinder. The respective distances between each transverse cylinder and the main cylinder were used to induce oblique shedding of different angles, curved shedding, as well as parallel shedding. Measurements of the mean static pressure distribution in the base region of the cylinder and of the mean spanwise component of the velocity in the wake were taken. These measurements revealed that a non-symmetric pressure distribution, which induced a spanwise flow in the base region of the cylinder, was responsible for the oblique shedding. By using a simple model based on the ratio of the streamwise to the spanwise vorticity components, the angle of shedding was predicted within 2^o of the value measured from flow visualization. The vorticity was simple evaluated from the spanwise and streamwise velocity profiles of oblique vortex streets obtained with the LDV measurements technique. Parallel vortex shedding showed a symmetric pressure distribution with zero spanwise component of the velocity and zero cross-shear in the cylinder base. It was shown that parallel vortex shedding results in a continuous Strouhal-Reynolds number curve.

6. Application of the wavelet analysis to the wake three dimensionalities caused by a local discontinuity in cylinder diameter

The wake three-dimensionality caused by a local discontinuity in cylinder diameter (a stepped cylinder) was studied. Changes in vortex shedding frequency caused by the discontinuity took place in either a direct or an indirect mode, depending on the diameter ratio and the Reynolds number. The roles of oblique shedding and frequency modulation of vortex shedding were studied. The physical change in vortex shedding frequency occurred differently for each mode. A wavelet analysis is used to explore frequency modulations in the wake. The relationship between vortex linkages, frequency changes, secondary

instability, and these two modes is discussed.

7. The Near-Field Dynamics and Entrainment Field of Submerged Jets

The recently observed persistence of ship wakes in open ocean observations has shown that there are fundamental changes in the dynamics of free shear layers near a free surface. This work presents an experimental investigation on the effect of a free surface on the near-field behavior of a round jet. The work focuses on the interaction between the vortex dynamics and entrainment characteristics of both submerged and near-surface jets.

The transition in round jets is accompanied by the transport of azimuthal to streamwise vorticity in the near-field of the flow. In free shear layers, this forms Bernal-Roshko structures which are streamwise vortex pairs. Similar structures are shown to exist in round jets. The primary structures, vortical rings, develop azimuthal or secondary instabilities as they move downstream. The resulting radial component of vorticity in the flow is tilted backward and stretched by the axial shear in the braid region of the flow. As the vortex filaments stretch backward, the vorticity increases and the induced velocity of the resulting vortex pair moves it farther outward, away from the shear layer into the stagnant fluid. The streamwise vortex pair is left behind the braid and forms a streamer-like structure. These streamwise structures were shown to sustain the far field entrainment field of the round jets.

8. A multi-point dual sheet laser doppler anemometer

A multi-point single component laser Doppler anemometer has been developed based on the interference pattern created at the line cross-section of two monochromatic polarized laser light sheets. The Doppler signals from up to 25 points can be sampled simultaneously

by an avalanche photodiode array. High signal to noise ratio processing of the Doppler signal can be achieved by interfacing each element of the photodiode array with a FFT based processor, rather than with a frequency tracker or counter processor.

9. Digital particle image velocimetry

Digital particle image velocimetry (DPIV) is the digital counterpart of conventional laser speckle velocitmetry (LSV) and particle image velocimetry (PIV) techniques. In this novel, two-dimensional technique, digitally recorded video images are anlyzed computationally, removing both the photographic and opto-mechanical processing steps inherent to PIV and LSV. The directional ambiguity generally associated with PIV and LSV is resolved by implementing local spatial cross-correlations between two sequential single-exposed particle images. The images are recorded at video rate (30 Hz or slower) which currently limits the applications of the technique to low speed flows until digital, high resolution video systems with higher framing rates become more economically feasible. Sequential imaging makes it possible to study unsteady phenomena like the temporal evolution of a vortex ring described in this paper. The spatial velocity measurements are compared with data obtained by direct measurement of the separation of individual particle pairs. Recovered velocity data are used to compute the spatial and temporal vorticity distribution and the circulation of the vortex ring.

10. Digital particle image thermometry: the method and implementation

A computerized flow visualization technique capable of automatically quantifying the temperature field in a two-dimensional cross section of a flow field is described. The temperature sensors used are fast-response temperature-sensitive micro-encapsulated liquid

crystal particles. Illuminating the flow by a thin sheet of white light, the reflected colors from the liquid-crystal particles were captured through a 3-chip video color camera and stored onto a videotape for subsequent data processing. The temperature field was obtained through an automatic color-temperature calibration scheme in *HSI* rather than *RGB* space, thus allowing for data processing of approximately one-third the time of *RGB* processing. The technique is finally applied to the study of a heated vortex-ring and some preliminary results are discussed.

11. Three-dimensional particle imaging with a single camera

A new approach to the instantaneous three-dimensional mapping of flow fields is introduced. A single camera system uses defocusing in conjunction with a mask (three pin holes) embedded in the camera lens to decode three-dimensional point sources of light (i.e., illuminated particles) on a single image. The sizes and locations of the particle image patterns on the image plane relate directly to the three-dimensional positions of the individual particles. Using sequential images, particles may be tracked in space and time, yielding whole-field velocity information. Calibration of the system is straightforward, whereas the self-similarity of the particle image patterns can be used in automating the data-extraction process. The described technique was used to obtain particle trajectories in the flow field of a vortex ring impinging on a wall.

Publications for URI

1. Gharib, M., B. Dyne, O. Thomas and C. Yap, "Flow Velocity Measurements by Image Processing of Optically Modulated Tracers," AGARD Conference Proceeding CPP-413, Paper No. 413, October 1986, 6 pp.
2. Van Atta, C.W. and M. Gharib, "Ordered and Chaotic Vortex Streets Behind Circular Cylinders at Low Reynolds Numbers," *J. Fluid Mech. 174:* (1987), 113-133.

3. Aref, H., M. Gharib and C.W. Van Atta, "Chaos in Shear Flows," AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference (Honolulu, Hawaii, June 1987), Paper No. 87-1251, AIAA, New York, 1987, 4 pp.

4. Van Atta, C.W., M. Gharib, and M. Hammache, "Three-dimensional Structure of Ordered and Chaotic Vortex Shedding behind Circular Cylinders at Low Reynolds Numbers," (A) *Proceedings of the IUTAM Symposium on Fundamental Aspects of Vortex Motion* (Tokyo, Japan, August-September 1987) North Holland Pub. Co., Amsterdam, 1988; also (B) *Fluid Dynamics Research 3*: 1-4 (1988), 127-132.

5. Gharib, M., and C. Willert, "Particle Tracing: Revisited," *(A) AIAA/ASME/SIAM/APS lst National Fluid Dynamics Congress, July 25-28, 1988, Cincinnati, Ohio, AIAA, Washington, D.C. 1988, Paper No. AIAA-88-3776-CP, 1935-1943. (B) Chapter 3, *Advances in Experimental Fluid Mechanics, Lecture Notes in Engineering,* Vol. 37, Springer-Verlag, 1989, 109-126.

6. Stuber, K. and M. Gharib, "Experiments on the forced wake of an airfoil," *J. Fluid Mech. 208* (1989), 225-255.

7. Willert, C. and M. Gharib, "A new video technique to capture images generated by a smoke wire," *Experiments in Fluids 8* (1989), 236-237.

8. Williams-Stuber, K. and M. Gharib, "Study of the origin of three-dimensional structures and chaos in an externally-forced free shear layer" (AIAA 2nd Shear Flow Conference, 1989, Tempe, AZ), AIAA, Washington, D.C. Paper AIAA 89-1021, 12 pp.

9. Hammache, C. and M. Gharib, "A novel method to promote parallel vortex shedding in the wake of circular cylinders," *Physics of Fluids A 1*:10 (1989), 1611-1614.

10. Williams-Stuber, K. and M. Gharib, "Transition from order to chaos in the wake of an airfoil," *J. Fluid Mech. 213* (1900), 29-57.

11. Williams-Stuber, K. and M. Gharib, "Experimental observation of chaos in free-mixing layers," *Proceedings of the Third Joint ASCE/ASME Mechanics Conference, Forum on Turbulent Flows* (La Jolla, California, July 1989), FED (Series), Vol. 76, ASME, New York, 1989, 24 pp.

12. Gharib, M. and D. Greene, "Simultaneous Flow Velocity and Temperature Measurements by Image Processing of Optically Modulated Temperature Sensitive Liquid Crystal Tracers," *Proceedings of the ASME Winter Annual Meeting* (December, 1987, Boston, MA), ASME, N.Y., 6 pp.

13. Elgar, Steve, Van Atta, C.W. and Gharib, M. "Bispectral Analysis of Ordered and Chaotic vortex Shedding from Vibrating Cylinders at Low Reynolds Numbers," *Physica D 39* (1989), 281-286.

14. Elgar, S., C.W. Van Atta and M. Gharib, "Cross-Bispectral Analysis of a Vibrating Cylinder and Its Wake in Low Reynolds Number Flow," *Journal of Fluids and Structures 4* (1990), 59-71.

15. Stuber, K. and M. Gharib, "Experiments on the forced wake of an airfoil transition from order to chaos," 1st National Fluid Dynamics Congress, (Cincinnati, Ohio, July 1988), AIAA, Washington, D.C., 1988, Paper No. AIAA 88-3840-CP, 723-730

16. Hammache, M. and M. Gharib, "A Novel Method to Promote Parallel Vortex Shedding in the Wake of Circular Cylinders," *Bull. Am. Phys. Soc. 34*::10 (November 1989), 2260-2261.

17. Willert, E. and M. Gharib, "Digital Particle Image Velocimetry," *Bull. Am. Phys. Soc. 34*::10 (November 1989), 2266.

18. Dabiri, D. and M. Gharib, "Digital Particle Image Thermometry," *(A) *Proceedings of the Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurements* (Lisbon, Portugal, July 1990), Instituto Superior Téchnico, Lisbon, Portugal, 1990, Session 2, Paper 1, 6 pages; also (B) in *Application of Laser Techniques in Fluid Mechanics*, J. Whitelaw (Ed.), Special Volume by Springer-Verlag, expected January 1991, 6 pages.

19. Papanicolaou, P. and M. Gharib, "A Multi-Point Dual Sheet Laser Doppler Anemometer," *Proceedings of the Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurements* (Lisbon, Portugal, July 1990), Instituto Superior Téchnico, Lisbon, Portugal, 1990, Session 5, Paper 4, 6 pages.

20. Willert, C. and M. Gharib, "Digital Particle Image Velocimetry Applied to an Evolving Vortex Ring," *Proceedings of the Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurements* (Lisbon, Portugal, July 1990), Instituto Superior Téchnico, Lisbon, Portugal, 1990, Session 18, Paper 1, 6 pages.

21. Hammache, M. and M. Gharib, "An Experimental study of the parallel and oblique vortex shedding from circular cylinders," *J. Fluid Mechanics 232:* (1991), 567-590.

22. Lewis, C. and M. Gharib, "Application of the wavelet transform to a frequency-modulated wake," USA French Workshop on "Wavelets and Turbulence". (Princeton University, June 1991), 21 pages.

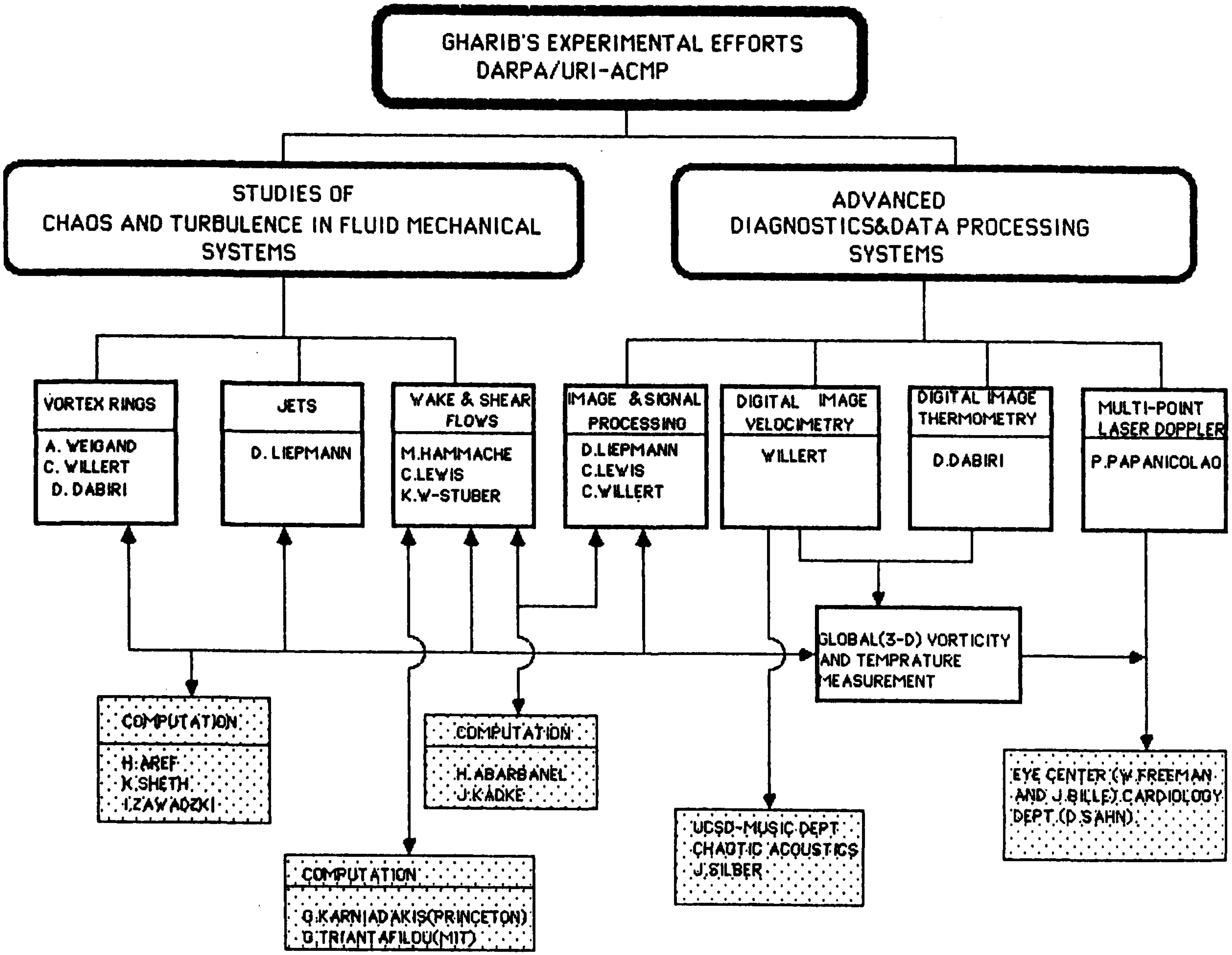
23. Gharib, M., C. Willert and D. Dabiri, "A Three-Dimensional Particle Imaging Technique for Simultaneous Velocity and Temperature Measurement," *Proceedings of the International Conference on Experimental Fluid Mechanics* (Chengdu, China, June 1991), 6 pages.

24. Willert, C.E. and M. Gharib, "Digital Particle Image Velocimetry," *Experiments in Fluids 10:* (1991), 181-193.

25. Dabiri, D. and M. Gharib, "Digital Particle Image Thermometry: The Method and Implementation," *Experiments in Fluids 11* (1991), 77-86.

26. Lewis, C.G. and M. Gharib, "An Exploration of the Wake Three Dimensionalities Caused by a Local Discontinuity in Cylinder Diameter," *Physics of Fluids A 4*::1 (1992), 104-117.

27. Willert, C. and M. Gharib, "Three-dimensional Particle Imaging with a Single Camera", *Experiments in Fluids*, 16 pages.


GHARIB'S EXPERIMENTAL EFFORTS
DARPA/URI-ACMP
STUDIES OF
CHAOS AND TURBULENCE IN FLUID MECHANICAL
SYSTEMS
ADVANCED
DIAGNOSTICS&DATA PROCESSING
SYSTEMS
VORTEX RINGS
A. WEIGAND
C. WILLERT
D. DABIRI
JETS
D. LIEPMANN
WAKE & SHEAR FLOWS
M.HAMMACHE
C.LEWIS
K.W-STUBER
IMAGE & SIGNAL PROCESSING
D.LIEPMANN
C.LEWIS
C.WILLERT
DIGITAL IMAGE VELOCIMETRY
WILLERT
DIGITAL IMAGE THERMOMETRY
D.DABIRI
MULTI-POINT LASER DOPPLER
P.PAPANICOLAO
GLOBAL(3-D) VORTICITY
AND TEMPRATURE
MEASUREMENT
COMPUTATION
H.AREF
K.SHETH
I.ZAWADZKI
COMPUTATION
H.ABARBANEL
J.KADKE
COMPUTATION
G.KARNIADAKIS(PRINCETON)
G.TRIANTAFILOU(MIT)
UCSD-MUSIC DEPT
CHAOTIC ACOUSTICS
J.SILBER
EYE CENTER (W.FREEMAN
AND J.BILLE) CARDIOLOGY
DEPT.(D.SAHN)

Final Report on URI - H. Levine

The URI supported research on a variety of problems related to the non-equilibrium behavior of both solids and liquids.

1) Developed computational approach to alloy solidification which can predict microstructural length scale and patterns. This was applied to eutectic growth, rapid solidification processing and the onset of dendritic branching during zone refining.

   Papers:

   Kessler, David and Levine, Herbert, "Steady-State Cellular Growth in Directional Solidification", *Phys. Rev.* **A39**, pg. 3041 (1989).

   Kessler, David and Levine, Herbert, "Computational Approach to Steady-State Eutetic Growth", *J. Cryst. Growth* **94**, 871 (1989).

   Kessler, D.A. and Levine, H., "Linear Stability of Directional Solidification Cells", *Physical Review A* **41**, pg. 3197, (1990).

   Levine, H., Rappel, W.J., and Riecke, H., "Resonant Interactions and Traveling-Solidification Cells", *Physical Review A* **43**, pg. 1122, (1991).

   Levine, H. and Rappel, W.J., "Oscillitory Instability in Rapid Solidification", *J. de Physique. I*, **V1** N9: 1291 (1991).

   Student: W. J. Rappel, Ph.D., 1991

2) Theoretical framework for the evaluation of disordered, fractal structures seen in multiphase flow, using ensemble averaging technique. Applied to three dimensional flow in a continued geometry. Work is currently being extended to more realistic models, for application to enhanced oil recovery.

   Papers:

   Brener, E., Levine, H. and Tu, Y., "Mean Field Theory for DLA in Low Dimensions", *Phys. Rev. Lett.* **66**, 1978 (1991).

   Kessler, D., Levine, H. and Tu, Y., "Interface Fluctuations in a Random Media", *Phys. Rev.* **A43**, 4551 (1991).

   Levine, H. and Tu, Y., "Mean Field Diffusion-Limited-Aggregation in Radial Geometries", *Phys. Rev. A*.

   Student: Y.H. Tu, Ph.D., 1991

3) Numerical predications for bubbles of air rising in fluid in the large bubble inviscid limit. Results on spherical cap bubbles agree remarkably well with experimental findings.

Papers:

Levine, H. and Yang, Y.M., "A Rising Bubble in a Tube", *Physics of Fluids A-Fluids Dynamics* **2**, pg. 542, (1990).

Yang, Y.M. and Levine, H., "Spherical Cap Bubbles", *J. Fluid Mech.*.

Student: Y. Yang, Ph.D., 1990

4) Began work on applying modern ideas of non-equilibrium dynamics to a variety of problems in chemical physics. These include

a) Waves seen during CO catalysis

b) Spiral patterns seen in redox reactions

c) Dendritic growth of phospholipid monolayers

Papers:

Kessler, D. and Levine, H., "Spiral Selection as a Free Boundary Problem", *Physica D* **49**, 90 (1991).

Levine, H. and Zou, Z., "Planar Travelling Waves in the Oscillatory Oxidation of CO over Polycrystalline", *J. Chem. Phys.* **V95** N5: 3815 (1991).

Kessler, D. and Levine, H., "Maximal Dendrite Size in Monolayer Systems", *Phys. Rev. Lett.* **V67**, N22: 3121 (1991).

Students: W. Reynolds (partial support), X. Zou

In addition to student support, the URI funded a one year visit by E. Brener from the Institute of Solid-State Physics, Moscow, who collaborated with our group on problems 1) and 2).

JOHN MILES

URI FINAL REPORT

Research supported by the URI contract has been reported in the following published papers, for which I was the sole author except as noted.

"Parametrically excited, standing cross-waves," *J. Fluid Mech.* **186**, 119-127 (January, 1988)

(with Janet Becker) "Parametrically excited, progressive cross-waves," *J. Fluid Mech.* **186**, 129-146 (January 1988)

"The evolution of a weakly nonlinear, weakly damped, capillary-gravity wave packet," *J. Fluid Mech.* **187**, 141-154 (February, 1988)

"Guided surface waves near cutoff," *J. Fluid Mech.* **189**, 287-300 (April, 1988)

"Resonance and symmetry breaking for a nonlinear oscillator," *Physics Letters A* **130**, 276–278 (July, 1988)

"Resonance and symmetry breaking for the pendulum," *Physica D* **31**, 252–268 (August, 1988)

"Directly forced oscillations of an inverted pendulum," *Phys. Lett. A* **133**, 295–297 (November, 1988)

"Edge waves on a gently sloping beach," *J. Fluid Mech.* **199**, 125–131 (February, 1989)

"The pendulum from Huygens' *Horologium* to symmetry breaking and chaos," *Proceedings of the XVII'th International Congress of Applied Mechanics in Grenoble*, 22–27 August 1988 (March, 1989)

"Resonance and symmetry breaking for a Duffing oscillator," (with an Appendix by P.J. Bryant) *SIAM J. Appl. Math* **49**, 968–981 (June, 1989)

"On the resonant response of a weakly damped, nonlinear oscillator," *J. Sound and Vibration* **131**, 489–496 (June, 1989)

"Symmetries of internally resonant, parametrically excited surface waves," *Phys. Rev. Lett.* **63**, 1436 (September, 1989)

"A complement of Weber's integral," *SIAM Rev.* **31**, 675–676 (December, 1989); **32**, 683–684 (December, 1990)

(with D. Henderson) "Parametrically forced surface waves," *Ann. Rev. Fluid Mech.* **22**, 143–165 (January, 1990)

"Wave motion in a viscous fluid of variable depth," *J. Fluid Mech.* **212**, 365–372 (March, 1990)

(with D. Henderson) "Single-mode Faraday waves in small cylinders," *J. Fluid Mech.* **213**, 95–109 (April, 1990)

"Parametrically excited standing edge waves," *J. Fluid Mech.* 214, 43–57 (May, 1990)

"Wave reflection from a gently sloping beach," *J. Fluid Mech.* 214, 59–66 (May, 1990)

(with P.J. Bryant) "On a periodically forced, weakly damped pendulum: Part 1: Applied torque," *J. Austral. Math. Soc. Ser. B* 32, 1–22 (July, 1990)

(with P.J. Bryant) "On a periodically forced, weakly damped pendulum: Part 2: Horizontal forcing," *J. Austral. Math. Soc. Ser. B* 32, 23–41 (July, 1990)

(with P.J. Bryant) "On a periodically forced, weakly damped pendulum: Part 3: Vertical forcing," *J. Austral. Math. Soc. Ser. B* 32, 42–60 (July, 1990)

"Richardson's number revisited," *Proceedings of the Third International Symposium on Stratified Flows in Pasadena, CA on February 3–5, 1987*, pp. 1–7. American Society of Civil Engineers, Somerset, New Jersey (July, 1990)

"Capillary-viscous forcing of surface waves," *J. Fluid Mech.* 219, 635–646 (October, 1990)

"The capillary boundary layer for standing waves," *J. Fluid Mech.* 222, 197–205 (January, 1991)

(with D. Henderson) "Faraday waves in 2:1 internal resonance," *J. Fluid Mech.* 222, 449–470 (January, 1991)

(with J. Becker) "Standing radial cross-waves," *J. Fluid Mech.* 222, 471–499 (January, 1991)

"Wave motion in a viscous fluid of variable depth, II: moving contact line," *J. Fluid Mech.* 223, 47–55 (February, 1991)

"Nonlinear asymmetric excitation of edge waves," *IMA J. Appl. Math.* 46, 101–108 (May, 1991)

"A note on surface films and surface waves," *Wave Motion* 13, 303–306 (May, 1991)

"On the initial-value problem for a wavemaker," *J. Fluid Mech.* 229, 589–601 (August, 1991)

"Variational approximations for gravity waves in water of variable depth," *J. Fluid Mech.* 232, 681–688 (November, 1991)

DARPA URI FINAL REPORT

C. M. Surko, Physics Department

The focus of the research was understanding the nature of traveling-wave convection in binary fluid mixtures using the ethanol-water system as a prototype. Surko arrived at UCSD in November 1989 and received support from the URI from that time to the end of the program, principally for the support of students and postdoctoral researchers. The research focussed on two topics and, as described below, progress was made in both areas. The work described was also supported in part by the U. S. Department of Energy under grant number DE-FG03-90ER14148.

The research was undertaken with two motivations in mind. The physical system (convection in ethanol/water mixtures) provides a relatively ideal and well controlled non-equilibrium system in which to study traveling-wave phenomena. From a practical point of view, such doubly-diffusive phenomena occur in many physical systems. Understanding their behavior, therefore, is of considerable importance.

I. *Nature of Confined States of Traveling-Wave Convection:* The nature of non-linear traveling-wave states in an annular channel was studied in detail. This geometry approximates a system with periodic boundary conditions, thereby permitting detailed comparison to be made between the results of these experiments and recent theoretical predictions. The principal investigator and his collaborators had previously discovered states of localized traveling-waves in which regions of non-linear traveling-wave convection co-exist stably with regions of conducting fluid (ie., zero flow). This discovery raised raised several important questions, one of which is the physical mechanism by which the boundaries between convection and conduction remain stationary in the laboratory frame, and another is the nature of these non-linear traveling-wave states. In particular, while the amplitude of convection in confined states is comparable to that for states which fill the entire annulus (ie., uniform traveling-wave states), the frequency of the localized states is more than a factor of two higher than that for uniform states.

Precise shadowgraph measurements of the amplitude, wavenumber, and frequency of localized traveling-wave states of different sizes were made. These data were compared with the

results of numerical calculations done by Professor Manfred Lücke and his collaborators at Universität des Saarlardes in Germany. The simulations are 2D finite-difference calculations done assuming the Boussinesq approximation of the Navier-Stokes equation. The data indicated that the calculations were able to capture virtually all of the features of the convecting states which were observed. In particular, the amplitude of convection, the observed wavelengths, the variation of amplitude and wavelength across the traveling-wave states, and the frequency of the localized traveling-wave states were in good agreement with the predictions of the numerical calculations.

This agreement permitted examination of the mechanism by which the fronts between conduction and convection are motionless in the laboratory frame. The numerical calculations show that the phasing of time-dependent variations of the concentration field with respect to those of the velocity field give rise to dc currents of concentration. In the upper part of the channel, the current is in one direction and in a lower part of the channel it is in the opposite direction. Consequently, these currents build up a concentration gradient in front of the (localized) traveling-wave state, and this concentration gradient stabilizes the fluid layer against the invasion of traveling-wave convection. Thus, the boundary between convection and conduction is stabilized by an intrinsically dynamical phenomenon.

II. *Measurement of the Concentration Field.* The second topic of research was study of the concentration field. In collaboration with Professor Lücke's group, it was discovered that the simple optical technique of the shadowgraph, if done carefully, can give information about the concentration field. This arises because it has recently been discovered that the concentration field in traveling-wave convection is not sinusoidal, but is closer to a square wave, with the concentration alternating from roll to roll. Since the shadowgraph measures the lateral Laplacian of the optical index of refraction, it includes structure due to the sharp changes in the concentration field at the edges of the rolls. Consequently the shadowgraph image of traveling-wave convection has sharp features which can be identified with the lateral variations in the concentration field.

Precise measurements of the shadowgraph intensity were taken and compared in detail with the results of the numerical calculations. The experiments are in agreement with the prediction that, in traveling-wave convection, the left-right symmetry about

up-flow and down-flow boundaries is broken. As one increases the Rayleigh number, the traveling-wave states evolve continuously to stationary convection. Lücke's group predicted that, as this transition is approached the symmetry at roll boundaries would be restored. The experiments confirm this prediction, and they permitted a detailed study of the change in the concentration field as a function of Rayleigh number. These results show that we understand the simplest of traveling-wave convection states, (ie., those which are uniform in the lateral direction). This success has now made it possible to study of more complicated dynamical phenomena in convection in mixtures such as the space-time evolution and interaction of more than one localized traveling wave state.

PUBLICATIONS

D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, and P. Kolodner, "Transition from traveling-wave to stationary convection in fluid mixtures," *Phys. Rev. Lett.* **65**, 1431-1434 (1990).

C. M. Surko, D. R. Ohlsen, S. Y. Yamamoto, and P. Kolodner, "Confined states of traveling-wave convection," *Phys. Rev. A* **43**, 7101-7104 (1991).

K. D. Eaton, D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, W. Barten, M. Lücke, M. Kamps, and P. Kolodner, "Concentration field in traveling-wave and stationary convection in fluid mixtures," *Phys. Rev. A* **43**, 7105-7108 (1991).

D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, and P. Kolodner, "Pinning and long-time-scale behavior in traveling-wave convection," J. Stat. Phys. 64, 903-912, (1991).

K. D. Eaton, C. M. Surko, D. R. Ohlsen, S. Y. Yamamoto, and G. W. Baxter, "Traveling-wave convection in binary fluid mixtures," *Proceedings of the 9th Symposium on Energy Engineering Sciences*, Argonne National Labs (May, 1991).

ABSTRACTS (of Talks)

D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, and P. Kolodner, "Transition from traveling-wave to stationary convection in an annulus," *Bull Am. Phys. Soc.* **34** (19) 2272 (1989).

D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, and P. Kolodner, "Nonlinear traveling-wave convection in an annulus," *Bull Am. Phys. Soc.* **35** (3) 262 (1990).

S. Y. Yamamoto, D. R. Ohlsen, C. M. Surko, and P. Kolodner, "Transition from traveling-wave to stationary convection in fluid mixtures," *Bull Am. Phys. Soc.* **35** (10) 2281 (1990).

D. R. Ohlsen, S. Y. Yamamoto, K. D. Eaton, C. M. Surko, and P. Kolodner, "Confined states in traveling-wave convection," *Bull Am. Phys. Soc.* **35** (10), 2281 (1990).

D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, and P. Kolodner, "The role of mixing in traveling-wave convection," *Phys. Fluids A* **3** (5), 1468 (1991).

C. M. Surko, "Experimental studies of uniform and confined traveling wave states," (invited talk), *Bull. Am. Phys. Soc.* **36**, 998 (1991).

K. D. Eaton, D. R. Ohlsen, S. Y. Yamamoto, C. M. Surko, W. Barten, M. Lücke, and P. Kolodner, "Concentration field in traveling-wave and stationary convection in fluid mixtures," *Bull. Am. Phys. Soc.* **36** (10), 2689 (1991).

G. W. Baxter, K. D. Eaton, and C. M. Surko, "Traveling-Wave Eckhaus instability and propagating phase disturbances in a binary fluid mixture," *Bull. Am. Phys. Soc.* **37** (1), 737 (1992).

Chuck Van Atta

Results from DARPA URI support

LABORATORY SIMULATION OF BUOYANCY INFLUENCED TURBULENT MIXING IN THE ATMOSPHERE AND OCEAN

Summary

Laboratory experiments were carried out in stably stratified shear flows simulating those that occur in the ocean. The experi· ents were done in several sheared and unsheared flows in both water and ..r.

The measurements of Todd Barrett in decaying turbulence in salt-stratified water used 2-component laser Doppler anemometry to measure velocity fluctuations and laser induced fluorescence to measure density fluctuations. Use of these optical measurement techniques was made possible by matching the indices of refraction of the different density layers used to obtain the continuous stratification. The experiments were carried out by towing a grid through the fluid, and extended to much larger Nt values(where N is the Vaisala frequency) than any previous studies. New decay laws for fluctuations and buoyancy fluxes were found for the largest buoyancy times, and used to extend the scope of oceanographic estimates from microstructure measurements. The ensemble averaging measurement technique used (data were averaged over 100 tows of the grid) allowed clear delineation of the internal wave field as well as the turbulence.

A thermally stratified wind tunnel was developed by John Lienhard as part of his Phd thesis. This unique facility makes it possible to obtain high quality measurements in unsheared density stratified flows in air. The tunnel was first used by Lienhard to study the decay of unsheared turbulence in thermally stratified air, complementing the salt-stratified water experiments of Stillinger et al (1983) and Itsweire et al. (1987) , but in a fluid with a Prandtl or Schmidt number nearly two thousand times smaller. The results (figure 27 of Lienhard and Van Atta, 1990) showed a strong Prandtl number dependence of the normalized buoyancy flux. Together with the salt-stratifed data, these results bracket the buoyancy flux range to be expected in the oceanographically crucial case of temperature in water (P_r =7). In the restratification region of the flow the cospectra of the buoyancy flux (figure 20 of L&V) showed a down-gradient buoyancy flux associated with turbulent mixing at small scales and simultaneous countergradient mixing at large scales, the first clear experimental evidence for such behavior.

These data are used by physical oceanographers in estimating buoyancy fluxes in the ocean and the general state of mixing from ocean microstructure data. Direct buoyancy flux measurement are not yet possible under oceanic conditions, despite recent progress summarized by Moum (1990). Using scaling and our laboratory data, Ivey and Imberger (1991) , and more recently Luketina et al (1991) have devised schemes to compute the diapycnal density flux from ocean dissipation measurements without employing the usual assumption of a constant mixing efficiency or flux Richardson number R_f. These syntheses and parameterizations are an important step in obtaining useful oceanographic mixing estimates, but the parameterization needs improvement on several accounts. This will require serious investigations of several key problems and fundamental questions which remain unanswered.

Two other new experimental facilities were under development during the grant. A two stream stably stratified mixing layer was completed by student David Schowalter. This is presently being used for experiments to extend our

earlier homogeneous turbulence results to a nonhomogenous shear flow simulating "billow" turbulence in the ocean and atmosophere. Measurements by Schowalter are presently underway to characterize the flows obtained in this facility and to develop new optical techniques for measuring velocity and density fluctuations in this flow.

The third facility under development during the grant is a uniform gradient stably stratified homogeneous shear flow air tunnel , which has been designed by student Paul Piccirillo and is presently under construction . It will use 70 kW of power to stably stratify the shear flow produced by the merging of the ouputs of ten independent blowers . This facility will make it possible to perform experiments like those of Rohr et al (1988), but with much greater control over the velocity and density profiles, Richardson and Reynolds numbers, and provide more accuracy and stability in the measurements. The lower Prandtl number will allow us again, comparing with the salt stratified water data, to bracket the case of temperature in water.

Siggurdur Thoroddsen carried out work on several problems in stratified turbulence during his PhD work. The first was a study of the effect of initial conditions on the evolution of decaying stratified turbulence. He found that the evolution of the buoyancy flux was nearly independent of the generating mechanism , and that internal waves generated by the turbulence-producing grid were not a factor in determining the buoyancy flux evolution or the critical times and parameters for buoyancy induced transitions and extinction of turbulent mixing.This work is described in Thoroddsen and Van Atta (1991a) . As a byproduct of this work, Thoroddsen also discovered a surprisingly large effect of buoyancy on the dissipation scales of the turbulent scalar and velocity fields , a result of inherent physical interest as well as of importance for applications to flux estimates from ocean microstructure data. Analysis of the numerical simulation data of Riley et al (1981) showed that the same effect could qualitatively be seen there. These results, which are discussed in Thoroddsen and Van Atta (1991b,c), led to the reexamination of the question of local isotropy of the smallest scales of turbulent scalar and velocity fields by Van Atta (1991) and showed that experiments in a number of different shear flows will be needed to adequately address this problem. Further experiments are proposed herein. Thoroddsen and Van Atta (1991d) also used wavelet analysis for the first time to study the scale dependence of turbulent mixing and the restratification process . The results provide spatially localized information about the scales contributing to the buoyancy flux and density and velocity fluctuations . Although we found that our wavelet analysis was not crucial in understanding the physical processes in which we obtained our stationary data records, our experience suggests that wavelet analysis should be very useful for applications by physical oceanographers to nonstationary records from both dropped and towed instruments.

The current high level of interest in the oceanographic, fluid mechanics, and physics communities in exponential tails in probability density functions of scalar fields and their gradients prompted the study by Thoroddsen and Van Atta (1991e) of the influence of buoyancy forces on the probability density functions of density and velocity fluctuations, and on the product of vertical velocity and density, i.e. the instantaneous buoyancy flux. The density gradient pdfs were found to exhibit long robust exponential tails, a result not predicted by recent theoretical efforts. We also found that exponential tails in instantaneous flux distributions are a natural consequence of joint-normal statistics.

Finally, we have begun some experiments on the effects of spatially varying Vaisala frequency and mean strain on turbulent mixing in stably stratified

fluids. A new specially instrumented contraction section has been built and installed in the stratified wind tunnel and preliminary measurements on the evolution of the fluctuations and buoyancy flux have been made . The object is to simulate the influence of topographic variations and internal wave straining on the mixing.

Major Facilites developed under DARPA URI

a) Two-layer Stably stratified shear layer facilities

Our first two-layer stably stratified shear layer facility is now in operation . Based on our early results we are constructing a second facility with a wider test section, which will be run from the same supply resevoirs.

b) Continuous gradient stratified shear layer

Prototypes for a continuous gradient facility using ten independent supply layers are being designed and tested. This will replace the original facility used in the first two years of the URI .

Future directions enabled

URI first year equipment funding allowed us to develop and use nonintrusive optical techniques for single point velocity and density measurements in stratified flows using LDA and LIF, 2-dimensional full field density measurements using LIF, and three-dimensional particle tracking using fluorescent particles. This new experimental ability has made a major impact on our research directions under the URI and in closely related work done under NSF Oceanography sponsorship.

The URI facilitated exchange of ideas and information between physical oceanographers in several oceanographic institutions and in ONR and our students and faculty doing basic laboratory studies. This interaction resulted in wider application of basic principles in interpreting ocean data.

This success encouraged a proposal to ONR for continued funding of our laboratory work at UCSD , which was selected for funding at the recent SIO ONR site visit.

The impact of our laboratory experiments on interpretation of ocean microstructure measurements has been significant. Numerous citations and examples of use of our findings can already be found in the oceanographic literature and a number of other applications in more recent stuides are in press , under review , or in progress.

This favorable response indicates that small scale physical oceanographers have been looking for guidance for physical interpretations of what they can measure, and that they appreciate

the value of idealized laboratory experiments in helping to solve their problems.

Appendices :

a) Faculty involved : C. W. Van Atta

b) Students supported:
Dr. Todd Barrett
Dr Siggurdur Thoroddsen
David Schowalter
Dr Chee Yap

References

Fernando, H.J.S. 1991 Mixing in stratified Fluids, Ann. Rev. Fluid Mech. 23, 455-493

Gargett, A. 1988 The scaling of turbulence in the presence of stable stratification, J. Geophys. Res. 93, 5021

Gerz,T., Schumann,U., Elgobashi, S.E. 1988 Direct Numerical Simulation of Stratified Homogeneous Turbulent Shear Flows, J. Fluid Mech. 200, 563-594

Gerz, T. and schumann,U. 1991 Direct Simulation of Homogeneous Turbulence and Gravity Waves in Sheared and Unsheared Flows, in Turbulent Shear Flows 7, 27-45

Gregg, M.C. 1987 Diapycnal Mixing in the Thermocline: A Review. J. Geophysical Res. 92, 5249-5286

Holt, S.E. , Koseff,J.R. , & Ferziger, J.H. 1990 The evolution of turbulence in the presence of mean shear and stable stratification. In Seventh Symposium on Turbulent Shear Flows, Stanford. springer-Verlag, in press

Holt, S.E. , Koseff, J., and Ferziger, J. 1991 The Evolution and Structure of Homogeneous Stably Stratified Sheared Turbulence, submitted to J. Fluid Mehanics

Itsweire,E.C., Holt, S.E., Koseff,J.R. , and Ferziger, J.H. 1990 Direct Numerical Simulations of Stably-Stratified Sheared Turbulence: Implications for Ocean Mixing , in Proceeding for the Summer Program, Center for Turbulence Research, Stanford Univ.

Itsweire, E. and Helland, K.N. 1989 Spectra and Energy Transfer in Stably Stratified Turbulence, J. Fluid Mech. 207, 419-452

Ivey, G.N. and Imberger, J. 1991 On the Nature of Turbulence in a Stratified Fluid.1. The Energetics of Mixing, J. Phys. Oceanogr. 21, 650-658

Launder,B.E. 1975 On the Effects of a Gravitational Field on theTurbulent Transport of Heat and Momentum . J. Fluid Mechanics, 67, 569-581

Lienhard, J.H. and Van Atta,C.W. 1990 The Decay of Turbulence in Thermally Stratified Flow, J. Fluid Mech. 210, 57-112

Luketina, D.A., Ivey,G., and Imberger, J. 1991 Mixing Efficiency in Decaying Stratified Turbulence, in preparation

Maxworthy, T. and Caperan, P. private communication

Metais, O. , Herring, J.R. 1988 Numerical Simulations of Freely Evolving Turbulence in Stably Stratified Fluids, J. Fluid Mech. 202,117-148

Metais, O. and Lesieur, M. 1991 Spectral Large-Eddy Simulation of Isotropic and Stably-Stratified Turbulence, submitted to J.Fluid Mech.

Mills, R.R., and Corrsin, S.C. 1959 Effect of Contraction on Turbulence and Temperature Fluctuations Generated by a Warm Grid, NASA Memo 5-5-59W

Moum, J.M. , Caldwell, D.R., and Paulson, C.A. 1988 Mixing in the Equatorial Surface Layer, submitted to J. Geophys. Res.

Moum, J.M. 1990 The Quest for K-Rho-Preliminary Results from Direct Measurements of Turbulent Fluxes in the Ocean, J. Phys. Oceanogr. 20, 1980-1984

Peters, H., Gregg, M.C. , and Toole, J.M. 1988, On the Parameterization of Equatorial Turbulence , Geophys. Res. 93,1199-1218

Riley, J. ,Metcalfe, r., and Weissman, M. 1981 Direct Numerical Simulations of Homogeneous Turbulence in Density -Stratified fluids. In *Nonlinear Properties of Internal Waves* , AIP Conf. Proc. 76, ed. B.J. West , 79-112

Rohr, J.J., Istweire, E.C., Helland, K.N., and C.W. Van Atta 1988 Growth and Decay of Turbulence in a Stably Stratified Shear Flow, J. Fluid Mech. 195, 77-111

Thoroddsen,S. and Van Atta. C.W. 1991 The Influence of stable stratification on small-Scale Anisotropy and Dissipation in Turbulence, J. Geophys. Res. Oceans (in press)

Thoroddsen, S. and Van Atta, C.W. 1991 Wavelet Analysis of Turbulent Mixing in a Stably Stratified Fluid, DARPA-ONERA Workshop "Ondelettes (Wavelets) and Turbulence".

Uberoi, M. 1957 Equipartition of Energy and Local Isotropy in Turbulent Flows, J. Appl. Phys. 28, 1165-1170

Van Atta, C.W. 1991 Local Isotropy of the Smallest Scales of Turbulent Scalar and Velocity Fields, Proc. Roy. Soc. Lond. A 434,139-147

Publications Supported by DARPA URI

Barrett , T.K. & C.W. Van Atta 1991 Experiments on the Inhibition of Mixing in Stably Stratified Decaying Turbulence using Laser Doppler Amemometry and Laser-induced Fluoresence , Phys. of Fluids a 3 (5) , 1321-1332

Lienhard, J.H. and Van Atta,C.W. 1990 The Decay of Turbulence in Thermally Stratified Flow, J. Fluid Mech. 210, 57-112

Lienhard V, J.L. & Van Atta, C. W. 1990 Thermally Stratifying a Wind Tunnnel for Buoyancy Influenced Flows, Experiments in Fluids
Rohr, J.J., E. C. Itsweire, and C.W. Van Atta, 1988 An Investigation of the Growth of Turbulence in a Uniform Mean Shear Flow, J. Fluid Mech. 187,1-33
Rohr, J. , Itsweire, E., Helland, K., and Van Atta,C. 1988 Growth and Decay of Turbulence in a Stably Stratified Shear Flow , J. Fluid Mech. 195, 77-111
Thoroddsen, S. & Van Atta, C.W. 1991a Experiments on small-scale anisotropy and dissipation in stably stratified turbulence, to J. Geophys. Res. Oceans (in press)
Van Atta, C. W. 1991 Local isotropy of the smallest scales of turbulent scalar and velocity fields, Proc. Roy. Soc. A 434, 139-147

Submitted and in preparation

Thoroddsen, S. and Van Atta,C.W.

Thoroddsen, S. & Van Atta, C.W. 1991b Experiments on density gradients in stably stratified grid turbulence, to be submitted to J. Fluid Mech.
Thoroddsen, S. and Van Atta, C.W. 1991 Wavelet Analysis of Turbulent Mixing in a Stably Stratified Fluid, submitted to proceedings of DARPA-ONERA Workshop "Ondelettes (Wavelets) and Turbulence".
Thoroddsen, S. And Van Atta, C.W. 1991 Exponential Tails and Skewness of Density-Gradient PDF's in Stably Stratified Turbulence, submitted to J. Fluid Mechanics

YEARLY ACCOMPLISHMENTS

DARPA/URI STATUS REPORT

ACCOMPLISHMENTS 1989/90

1. Completion of a vortex-in-cell code and post-processing routines allowing simulation of vortices and passive tracer configurations in three dimensions.

2. Numerical experiments on the interaction of vortex rings, mixing during vortex ring collision, response of Hill's spherical vortex to general perturbations and modulation of shear layers by perturbations of different wavelengths.

3. Construction of a geometrical optics ray-tracing code with verification by computing analytically known reflection and refraction patterns, including caustics. Numerical experiments on ray patterns from "dynamically active" fluid surfaces such as a decaying vortex and a bubble at the fluid surface.

4. Research aimed at understanding of symmetry breaking, pattern selection, and dissipation in nonlinear wave motion that has been reported in seven papers accepted by refereed journals. In addition, 10 papers reporting URI-supported work in previous years have been published during the past fiscal year.

5. We have developed an understanding of confined states of binary fluid convection via experimental determination of the concentration profile.

6. We have established methods for taking "pseudo" experimental data and removing noise, reconstructing the attractor, and calculating some of the dynamically invariant quantities that identify the attractor. Furthermore, we have used these results to develop algorithms that accurately predict the temporal evolution of points on the attractor, as well as reproduction of the dynamical invariants.

7. We have extended our analytical approach to interfacial patterns to include the effects of reflection symmetry breaking. This has been applied to solidification cells and to viscous fingering. Also, calculations have been performed to determine the shapes of bubbles rising in an infinite fluid and spiral waves in excitable chemical media.

8. Completed projects include digital particle image thermometry, digital particle velocimetry and a single camera three-dimensional velocimeter. Substantial progress was made on studies of instabilities and turbulent transition in jet flows and studies of wave interaction wakes.

9. Developed a number of analytic methods to deal with the Non-Markovian stochastic equations that arise in reaction rate theory.

URI Program UCSD

1989 Accomplishments

1989 Accomplishments: Found new mechanisms for vortex straightening in flow over elastic cylinders; can reduce chaos and prevent transition to turbulence. Found new routes to chaos in interaction of vortex streets with different Strouhal frequencies in laboratory flows. Developed new methods for analysis of surface phenomena in bubble dynamics and dendritic growth dynamics. Produced new methods for determining embedding dimensions for strange attractors and began to apply it to laboratory fluid dynamics data. Created new algorithms for classification and prediction for chaotic systems, including methods for getting all Lyapunov exponents from experimental data.

Milestones 1989/90 and 1990/91

1989/90:

(1) Laboratory investigations of vortex shedding and interaction in flows over graded and incommensurate cylinders.

(2) Dynamics and characterization of jets in volume flows by their surface signature.

(3) Interfacial dynamics in dendritic growth and bubble flows in cylinders.

(4) Development of prediction techniques for chaotic flows.

(5) Numerical studies of vortex evolution over complex bottom topography.

1990/91:

(1) Laboratory studies of bifurcations to chaos in convection of mixtures.

(2) Analysis of influences of vortex dynamics on drag in flows over elastic graded cylinders.

(3) Study of surface wave dynamics in basin and open ocean settings: Laboratory and theory.

(4) Application of prediction techniques for chaos to laboratory fluid flows and field data.

(5) Development of information theoretic methods for reduction of noise contamination of chaotic signals. Application of the methods to the analysis of noisy field and laboratory data.

Accomplishments for FY88 and Plans for FY89
DARPA/URI Program
University of California, San Diego

Henry D. I. Abarbanel
Principal Investigator

FY88 Accomplishments

- built and tested experimental research stand to investigate flow between rotating disks. Incorporated laser Doppler interferometer in the apparatus. Discovered nonperiodic flutter signals in the out-of-plane motion of the disks.

- investigated Hamiltonian dynamics on symplectic leaves. This is the Hamiltonian counterpart of the center manifold theorem and is critical for the investigation of bifurcations in inviscid fluid flows.

- developed amplitude equations for the growth and nonlinear saturation of instabilities in multiphase flows.

- analyzed the nonlinear dynamics of driven, spherical bubbles. In conjunction with this developed numerically efficient 'cell-mapping' methods for the analysis of dynamical properties of fluid flows.

- discovered the phenomenon of 'bubble chasing'. This is a situation where two nearby bubbles in suspension produce hydrodynamic forces on each other which causes them to create local vortex motions.

- Developed models of vortex structure interactions. Applications are to vibrations of beams and airfoils in interaction with turbulent flows.

- Developed new numerical methods for the evolution of free and bound waves on the nonlinear ocean surface. These replace spectral methods which diverge numerically.

- Investigated resonance and symmetry breaking in cross waves in a wave tank and studied pattern selection for parametrically excited surface waves on the ocean.

- Developed methods for three dimensional particle tracing in fluid experiments.

- Built and tested automatic field temperature measurement techniques for heat transfer experiments.

- Investigated experimentally the phenomenon of chaotic vortex reconnection.

- Developed new techniques for the analysis of stable solutions of the Euler equations in two dimensions. These are relevant to the development of chaos and turbulence in geophysical flows. Numerical and analytic methods have been developed.

- Developed theories for rising bubbles. The investigation of the role of surface tension in determining the rise velocity has been the focus of the work.

- Derived the amplitude equations governing the development of cross-waves driven by axisymmetric wavemakers.

- Developed models for the interface between turbulent and nonturbulent flows and applied it to the decay and description of wakes generated by bodies in motion in a

fluid. The models were developed in connection with ongoing experiments under the URI program.

- Discovered a new family of algorithms that reduce any flow to the nearest stable stationary flow.
- Investigated the stability of modons ['solitons' in geophysical flows] under topographic perturbations. This represents the effect of ocean bottom topography on the stability of long lived oceanic features.
- Discovered new metastable states for barotropic flows over orography and in water wave dynamics.
- Investigated new methods for identifying stable states of two dimension point vortex flows. A remarkable connection to soliton solutions of the KdV equations has been found.
- Initiated the development of efficient numerical codes for the solution of the full navier-Stokes equations for flows between rotating disks.
- Created new efficient numerical techniques for extracting the fractional dimension of systems from experimental time series. Studied the properties of several measures of these invariant dimensions.
- Investigated experimentally the effect of small boundary layer ring manipulators on drag reduction around axisymmetric bodies.
- Studied experimentally the evolution of velocity and density fluctuations in stably stratified turbulent shear flows.

FY1987 Activities under DARPA/URI Program on Research and Education in Chaotic and Turbulent Fluid Dynamics

University of California, San Diego

September 28 1987

This is a brief report on the research activities of the investigators under the DARPA/URI Program in Fluid Dynamics. The attached material indicates the names of all investigators, the students and postdoctoral fellows who joining the Program in 1986-87, and a number of the visitors under the Program. For this note just the names of the personnel and their research progress are provided.

- Henry Abarbanel--(1) phase space density formulation of inviscid fluid dynamics and application to geophysical flows; (2) formulation of Hamiltonian dynamics of free boundary problems; (3) investigation of symmetry groups of inviscid fluid equations with calculation of invariants of the motion; for use in stability analysis of free boundary problems. Work done with R. Brown and J. Ariyasu, URI postdocs, and Y. M. Yang, a URI graduate student.

- Hassan Aref--(1) Vortex dynamics and vortex patterns in steady motion; chaotic scattering of vortex pairs. (2) Chaotic advection--chaos as a vehicle for efficient stirring of laminar flows. (3) Phenomenological models for the turbulent-laminar interface--fractal behavior of the interface; in collaboration with P. Libby.

- Albert Ellis--Nonlinear dynamics of bubbles. Bubbles are trapped in a 10-khz acoustic wave and excited by higher frequency acoustic signals. Work in collaboration with Brooke-Benjamin of Oxford. Collaborations with two students supported by URI who are doing numerical calculations on nonlinear bubble dynamics. Also interacts with J. D. Crawford and H. Riecke [DARPA/ACMP researchers] on bifurcations of symmetric bubbles.

- M. Gharib--(1) Air Foil Wakes; found route to chaos in open systems through 3-frequency forcing. Applications to airplane wing design considered. (2) Fractal Geometry of Turbulence in jet Flows; found a fundamental connection between the growth of linear instabilities and the change in the fractal dimension of boundaries between turbulent and laminar flows--work with Aref and van Atta. (3) Aeroelastic Coupling as a source of Chaotic behavior in Flow-Structure Interactions; has shown that spatially chaotic flows can be produced in which ordered, quasi-periodic and chaotic regions of flow can coexist. (4) Use of Liquid Crystals for flow measurements; uses liquid crystals for simultaneous measurement of temperature and velocity fields.

- John Greene--work on two-dimensional area preserving maps; in particular higher order fixed points of renormalization operators for the maps. These maps are representative of Poincare sections of simple inviscid flows.

- Frank Talke--experimental work on flow and dynamics of read-write heads in rotating disc systems for magnetic recording. Analytic work in conjunction with Rotenberg and Libby. Experiments are complemented by extensive numerical calculations on the interaction between the mechanical dynamics and the fluid dynamics in these systems.

- Paul Libby--(1) stability of rotating flows; studying two rotating discs in a housing. Developed equations for mean flow and made asymptotic treatment of small spacing. This work is with F. Talke and M. Rotenberg. (2) Along with Aref is studying the dynamics of an interface between turbulent and laminar flow. The model involves 100 vortices to represent the flow. Will be compared to the experiments of Gharib and students.

- Katja Lindenberg--(1) application of statistical mechanical techniques to geophysical problems; barotropic flow over orography and surface wave dynamics. In conjunction with B. West; (2) Development of techniques for the implement these statistical methods. In particular, a new path integral techniques is used for the calculation of first passage times and for the statistics of flows driven by noise which is neither Gaussian nor white.

- John Miles--(1) Evolution of capillary-gravity wave packets; contributions to energy transfer in surface wave motions. (2) Guided surface waves near cutoff frequency; application to waves in channels. (3) Parametrically excited, standing cross waves; Hamiltonian dynamics of waves in tanks; energy transfer spectrum. (4) Parametrically excited, progressive cross waves [with student J. Becker]; application to surface waves; (5) Symmetry Breaking for the Duffing Oscillator; dynamical systems investigation of a model suggested by fluid problems. (6) Forced Oscillations of the pendulum; dynamics of a model problem suggested by stability of fluids in tanks. Miles has also sponsored experiments by students on waves in channels in the wave tank facility renovated with URI funds; these experiments are in conjunction with the theory being investigated by his students and himself.

- M. Rotenberg--dynamics of rotating disc flows; in collaboration with Talke and Libby. Pseudospectral methods are being used to make numerical calculations for these flows. Turbulence associated with the enclosure of these rotating discs are seen to be important and constitute a new feature of these calulcations. Experiments performed by Talke and students are to be compared to these calculations.

- Kenneth Watson--participating in an experiment to find deep water solitons. Working with graduate student from UCSD Physics

- Bruce West--works on projects with Lindenberg listed above. Also working on (1) application of random walk ideas to turbulent flows. (2) developed model of himself and Watson for interaction between long and short waves on the sea surface. Numerical techniques for studying this phenomenon have been developed.

- ALL INVESTIGATORS--(1) established graphics workplace equipped with SUN and IRIS graphics workstations and an Alliant FX/1 for intensive numerical calculations for the graphics displays. (2) chose five new URI postdoctoral fellows, from an applicants pool of 125, to work on experiments, theory, and calculations. (3) ran an extensive visitor program and planned a program for FY88 (4) ran a Winter School on fluid dynamics in March, 1987; planned a

similar school for January, 1988. School attended by 75 students from around the US. (5) Established extensive scientific collaborations with Government laboratories and industrial scientific workers. (6) ran a full URI seminar series in fluid dynamics and planned a similar one for FY88.

Absent from this list are George Carnevale, Charles Van Atta, and Geoffrey Vallis--all of whom were out of the country when this request came to us. vallis and carnevale are working on the dynamics of quasi-geostrophic flows over topography in the ocean and in the atmosphere. Van Atta, with his students, is performing experiments on the nature of turbulent stratified flows in laboratory conditions as well as working with Gharib on aeroelastic flow interactions.

We have, as promised in our proposal, added several new people to the URI Program. Evgeny Novikov has joined the effort as a Research Physicist; his work is on vortex flows and the structure of turbulence. he has demonstrated the solvability of the one dimensional shallow water equations. He also collaborates with Gharib in the interpretation of vortex dominated experiments. Herb levine has joined the Physics faculty under one of the faculty positions associated with the URI by UCSD. His work will be on pattern formation and dendritic growth. Also faculty offers have been made to two experimentalists, one in Physics and one in mechanical engineering, to join the URI effort at UCSD.